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Variational asymptotic homogenization of magneto-electro-elastic materials with coated fibers ☆

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ABSTRACT

The effective properties as well as local fields of heterogenous magneto-electro-elastic (MEE) materials with coated fibers are investigated by using the variational asymptotic homogenization method. Starting from the total electromagnetic enthalpy of the heterogenous continuum, the multiphysics micromechanics model is formulated as a constrained minimization problem taking advantage of the face that the size of the microstructure is small compared to the macroscopic size of the material. To treat general microstructure of smart material in engineering applications, this new model is implemented using finite element technique. A comparison with the finite element analysis (FEA) results demonstrates the application and accuracy of the proposed model for prediction of multiphysical behavior. The effects of the coating with different thickness and stiffness on the stress concentration factor and effective MEE properties are discussed and a lot of interesting MEE interaction phenomena are revealed, which are useful to estimate and optimize the performance of such MEE composites.

1. Introduction

With the development of modern science and new technology, magneto-electro-elastic (MEE) materials are widely used in aerospace, nuclear and electronic package, hydrophones, medical ultrasonic imaging, sensors and actuators due to the ability of converting magnetic, electric and mechanical fields together [1,2]. It is well known, owing to chemical reactions or man-made interface design, such as surface modification of reinforced phase by using coating in order to enhance wetting property or adjust interface residual stress [3], an interphase exists between the reinforced phase and the matrix in a practical composite system. Interphase properties are different from both the reinforced phase and the matrix. When the size of inclusions and coatings in composites is on the order of micrometer, the interface effect plays an important role in the macroscopic properties due to their high surface-to-volume ratios [4]. From the perspective of size, macroscopic characteristic size is on the order of millimeter, while micro-inclusions and interface characteristic size achieve micro-scale.

In pursuing understanding of the excellent performance and optimal design of MEE materials, the interface effect of such composites has been studied by many scholars from a fundamental perspective. Sharma et al. [5] reformulated the inhomogeneity problem to include the size dependent surface and interface effects on its elastic state. Sharma and Ganti [6] modified Eshelby's classical approach towards inclusions and inhomogeneities to incorporate the effect of surface energies via the continuum field formulation of surface elasticity. Yang et al. [7] analyzed the effect of surface energy on the effective elastic properties of composite materials containing spherical cavities at dilute concentration. Duan et al. [8] generalized the fundamental framework of micromechanical procedure to take into account the surface/interface stress effect on the effective elastic moduli of heterogeneous solids containing inhomogeneities. He and Li [9] applied the model proposed by Gurtin and Murdoch to account for the influence of surface stress on stress concentration near a spherical void in an infinite elastic solid. Lim et al. [10] examined the effect of interface effect on the elastic state of spherical inclusion with uniform, non-hydrostatic axisymmetric eigens strains. Chen [11] derived exact, size-dependent connections between the overall axisymmetric electroelastic moduli, and also between the effective thermal stress coefficients and the effective pyroelectric coefficient to the overall electroelastic moduli. Luo and Wang [12] applied semi-analytical method to investigate anti-plane shear of an

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Nomenclature

v_i, ψ^e, ψ^m	global exact displacement, electric potential and magnetic potential, respectively
u_i, ϕ^e, ϕ^m	global average displacement, electric potential and magnetic potential, respectively
χ_i, χ^e, χ^m	fluctuation function of displacement, electric potential and magnetic potential, respectively
Ω	volume occupied by the UC
$\sigma_{ij}, \varepsilon_{ij}$	3D stress and strain field, respectively
E_i, H_i	electric and magnetic field vectors, respectively
D_i, B_i	electric flux density vector and magnetic flux density vector, respectively
U	electromagnetic enthalpy
L, L^*	12×12 multiphysics matrix and effective multiphysics matrix, respectively
C	6×6 submatrix for elastic constants
e, q	6×3 submatrix for piezoelectric and piezomagnetic coefficients, respectively
k, a, μ	3×3 submatrix for dielectric, electromagnetic, and magnetic permeability coefficients, respectively
$\lambda_i, \lambda^m, \lambda^e, \alpha_i, \beta_i$	lagrange multipliers introduced to enforce the constraints
x_i, y_i, n_i	global, local and integer-valued coordinate, respectively
S	shape functions
N	column matrix of the nodal values of fluctuation functions
$2a_i$	dimension of a UC (Unit Cell)
S_i	surface normal to y_i
$\Omega_m, \Omega_c, \Omega_f$	volume occupied by matrix, coating and fiber, respectively
R_0, R_1	internal and external radius of the coating, respectively
$\bar{\varepsilon}$	global multiphysics field variable array with homogenized effective material properties
δ	non-dimensional thickness of coating
ϕ	fiber volume fraction
ε	multiphysical field vector

elliptic inhomogeneity embedded in an infinite matrix. Brisard et al. [13,14] applied variational framework for composites to the derivation of bounds on the bulk modulus and shear modulus.

To the best knowledge of authors, the micromechanics model for MEE materials with coated fibers is relatively rare in the existing literature. In this paper, a homogenization procedure for MEE materials with coated fibers is developed by using the variational asymptotic method of unit cell homogenization (VAMUCH). This method is based on the variational asymptotic method (VAM) introduced by Berdichevsky [15], which is applicable to any solid mechanics problem admitting a variational structure where one or more relatively small parameters are involved. The "smallness" of these parameters is exploited by using an asymptotic expansion structure of the functional of the problem (not of the unknown field quantities as done in conventional asymptotic methods). Thus, VAM combines the advantages of both variational (most notably FE structure) and asymptotic methods, which has been used earlier to model composite and smart beams (Yu et al. [16]), plates (Zhong et al. [17]) and shells (Zhong et al. [18]). Application of VAM for homogenization of media with periodic microstructures leads to the development of VAMUCH, which has been successfully applied so far for periodically heterogenous material (Yu, [19]), with thermoelastic properties (Yu, [20]). Recently, this method is applied for effective magnetostrictive property estimation of heterogenous materials (Zhong, [21]).

Since the present approach extends VAMUCH to MEE materials with coated fibers in the same framework, the author has chosen to repeat some asymptotic derivation formulae and results from the previous works in order to make the present approach more self-contained.

2. Statement of the problem

Fig. 1(b) shows the cross-section of MEE materials with coated fibers, in which x_i, y_i and n_i denote the global coordinates, the local coordinates and the integer coordinates, respectively (Here and throughout the paper, Latin indices assume 1, 2 and 3 and repeated indices are summed over their range except where explicitly indicated). The origin of the local coordinates y_i is chosen to be the geometric center of UC. For example, if the UC is a cube with dimensions as $2a_i$, then $y_i \in [-a_i, a_i]$.

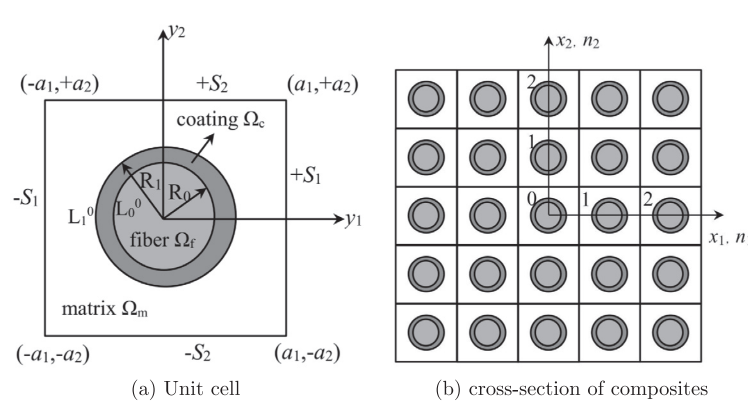

Fig. 1. Unit cell and cross-section of MEE materials.